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Measurements of Ground Vibrations Near Slab and Ballast Tracks – Influence of the Train Type, Train Speed, Soil, and the Track

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Abstract

Measurements of ground and track vibrations have been performed at a high-speed line in northern Germany. Impacts on the track and the ground, and passages of different trains with different speeds on different tracks have been measured. Transfer functions of the soil are presented and approximated by theoretical soil models. By using these transfer functions, the measured ground vibration between 4 to 64 m distance from the track can be transformed into a load spectrum which can be used for predictions at other sites. The method is compared to the soil-dependent method of an emission spectrum at a certain distance (8 m for example). Different trains yield different ground vibrations because of their different axle sequence. The first, second and third car length frequency could be clearly identified. Specific vibration components increase more than proportionally with increasing train speed between 200 and 320 km/h. A stiff slab track can reduce the low-frequency ground vibration compared to a ballast track. A high-frequency amplification of the slab track has been analysed with the dynamic vehicle-track interaction.

Keywords: ground vibration, axle sequence, train speed, soil transfer function, slab track, ballast track.

1 Introduction

Train-induced ground vibrations have been measured many times for ballast tracks, for example [1-4]. Measurements of ground vibrations from trains passing over slab tracks are, however, quite rare [5,6]. The Federal Institute of Material Research and

Testing had the opportunity to measure the ground vibration from both a ballasted and a slab track. Besides the characteristic differences between ballast and slab track, the measuring campaign yielded also influence of different trains, different train speeds and different soils. This article contributes several clear measurement results, but also several theoretical explanations to the state of the art. Calculated axle sequences of two train types, rules for the amplitude-speed relations, identified soil models of two sites, force distributions under a slab and ballast track and vehicle-track transfer functions with different resonances underline the experimental findings.

Slab track is a track form which becomes more and more usual. The specific behaviour of slab tracks has been investigated for ground vibrations, stiffness of the track, and settlements. Settlements [7] are one part of the track irregularities [4,8] which yield the dynamic loads [9]. These loads are the cause of subsequent settlements [10] as well as of the ground vibrations. The track stiffness is important for the dynamic vehicle-track interaction and its contribution to the ground vibration excitation [11]. The load distribution by the track is important for the settlements and for a specific low-frequency ground vibration called “scattered axle impulses” [12].

The contribution consists of the following sections. The first section shows the ground vibration of different trains and their different axle sequences. The second section presents some results for the influence of the train speed. The third section deals with the important influence of the soil and its consideration in measurements. The main part of the contribution compares the ground vibrations from ballast and slab tracks. First the experimental results are given. Next, a theoretical explanation for the low-frequency reduction is given, and in the last section, an explanation of the high-frequency amplification is given by the vehicle-track interaction.

2 Different trains with different axle sequences

The ground vibrations of different trains, an ICE3 train and a Thalys train, are

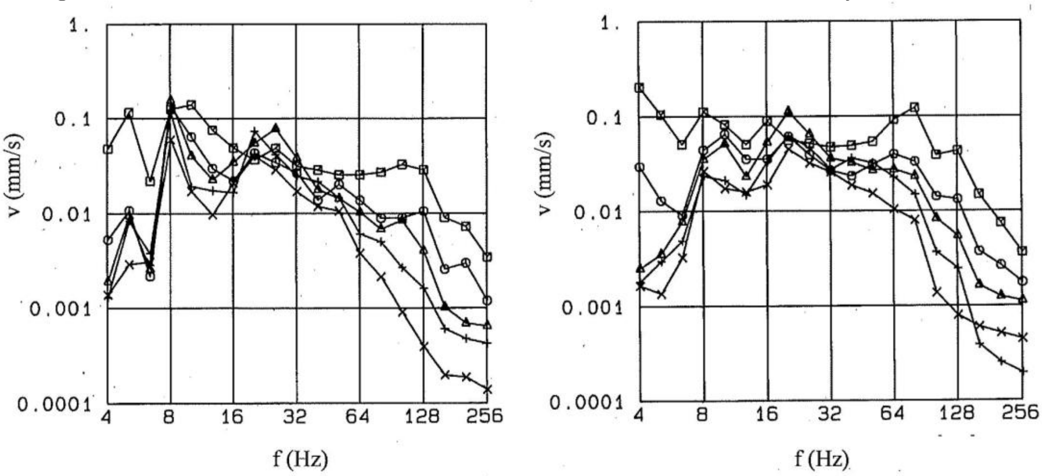

Figure 1: Measured ground vibrations at site 1 due to a) an ICE3 train, and b) a Thalys train, with train speed v_T = 250 km/h, one-third of octave band spectra at distances r = □ 4 m, ○ 8 m, △ 16 m, + 32 m, × 64 m.

presented in Figure 1 as one-third octave band spectra. Both trains run with 250 km/h and the corresponding amplitude level is almost the same. The high-frequency amplitudes of the Thalys train are somewhat higher what should be due to a worse wheel condition. The shape of the spectra at frequencies below 10 Hz are characteristic for each train. The peak at 8 Hz is much stronger for the ICE3 train. The Thalys train has a dominant peak at 4 Hz, the ICE3 a second peak at 5 Hz.

These peaks are related to the axle sequence of the train which are shown in Figure 2 as a time sequence and the corresponding linear spectrum. The ICE3 has a completely regular sequence of axles where all cars are the same. The corresponding spectrum shows regularly spaced peaks. The Thalys train, on the other hand, consists of engines, end cars and mid cars, all with different axle sequences. As a consequence, the spectrum is more irregular. In addition to the regularly spaced peaks, there are also wider bands, for example between 18 and 26 Hz.

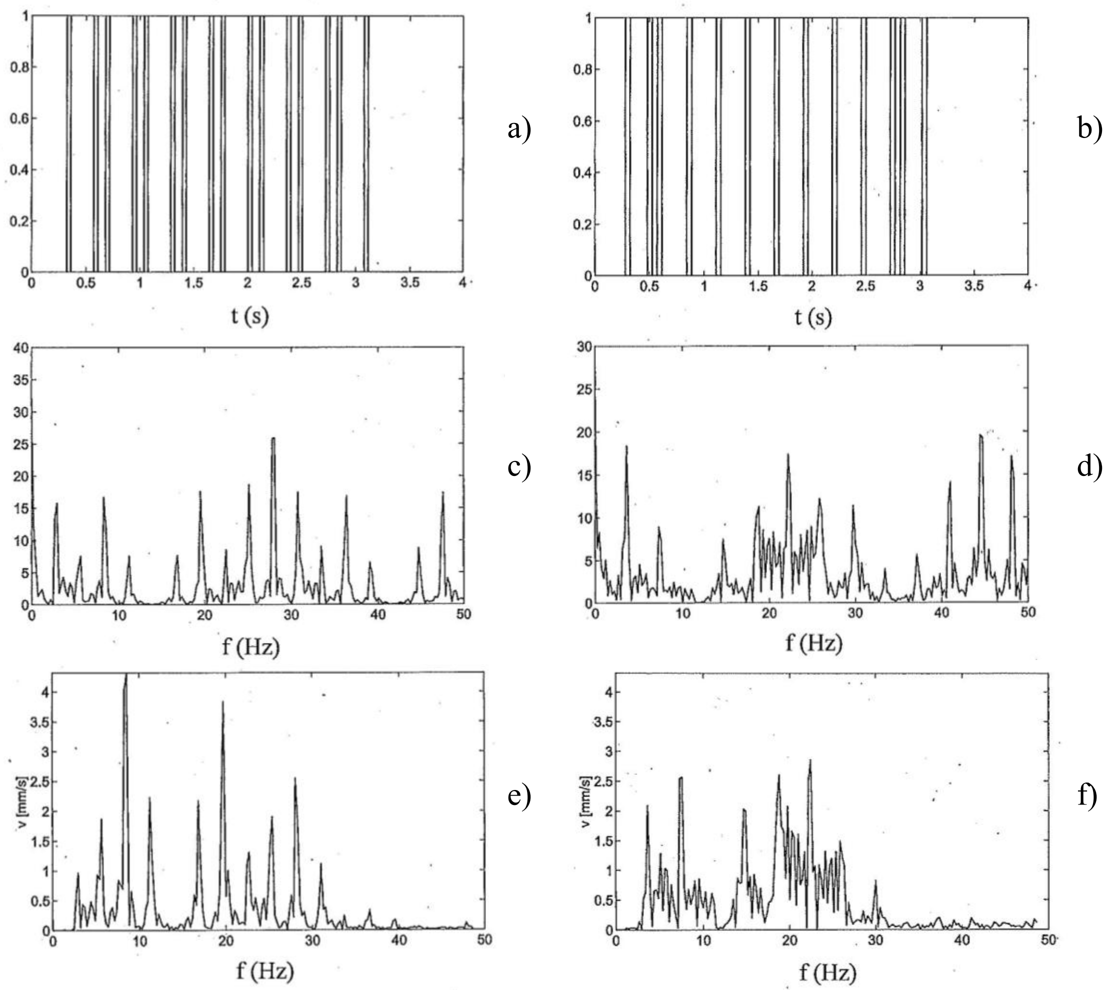

Figure 2: Axle sequence a,c,e) of the ICE3 train, and b,d,f) of the Thalys train, v_T = 250 km/h, a,b) in time domain, c,d) calculated in frequency domain, and e,f) measured at the sleeper in frequency domain.

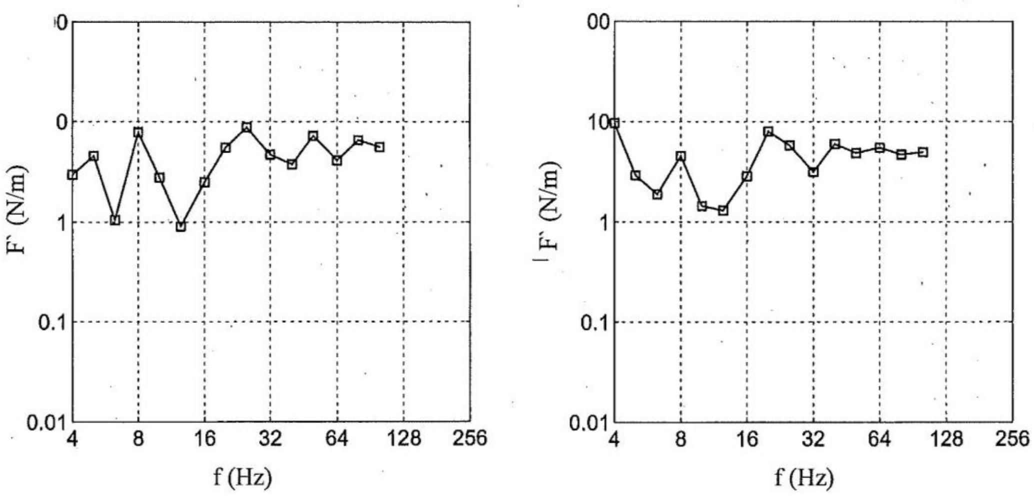

Figure 3: Axle-sequences a) of the ICE3 train, and b) of the Thalys train, v_T = 250 km/h, as one-third of otave band spectra.

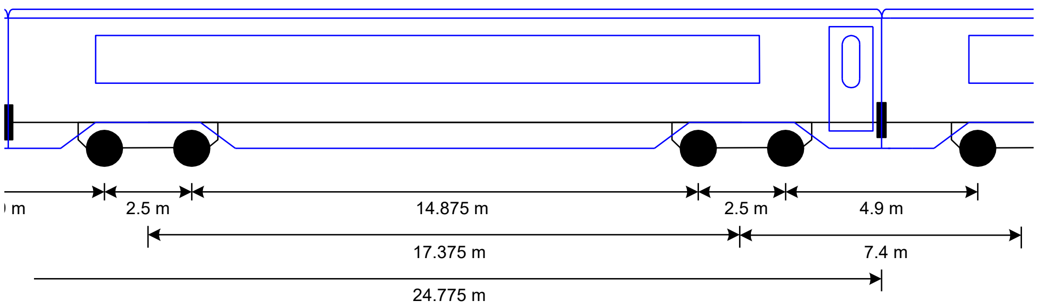

Figure 4: Axle distances of an ICE3 car. Only the car length (and multiples) yield a peak in the axle-sequence spectrum.

The regular peaks are the car distance frequency and multiples. As the Thalys train consists of shorter car, the car distance frequency is higher. The 8 Hz peak is the second car frequency of the Thalys train, but the third car frequency of the ICE3. Note that the car distance frequency is the only axle distance frequency which can be found in the axle sequence spectrum. In the one-third octave band spectra of Figure 3, the first, second and third car frequencies can be seen. The next characteristics are not maxima but two minima of the spectrum which are due to the distance of the two axles in a bogie [12]. These minima are at about 12 and 32 Hz for both trains.

Similar axle-sequence have been observed in investigating bridge resonances [13]. The spectrum of the bridge response to two different train passages is shown in Figure 5. The spectra represent quite clearly the axle sequence spectra of the different trains. The first train, the S103 is identical with the ICE3 and shows the first three clear car length frequencies. The third car frequency at 9 Hz excites the first bending mode of the bridge. The second train is a Talgo train which consists of two engines, two end cars and a number of mid cars. This irregularity yields similar irregular axle sequence spectra as the similar Thalys train or other non-periodic trains [14]. The second car frequency at 11 Hz excites the first torsional mode of the bridge. So, the axle sequence spectrum is even more important for bridges than for ground vibrations.

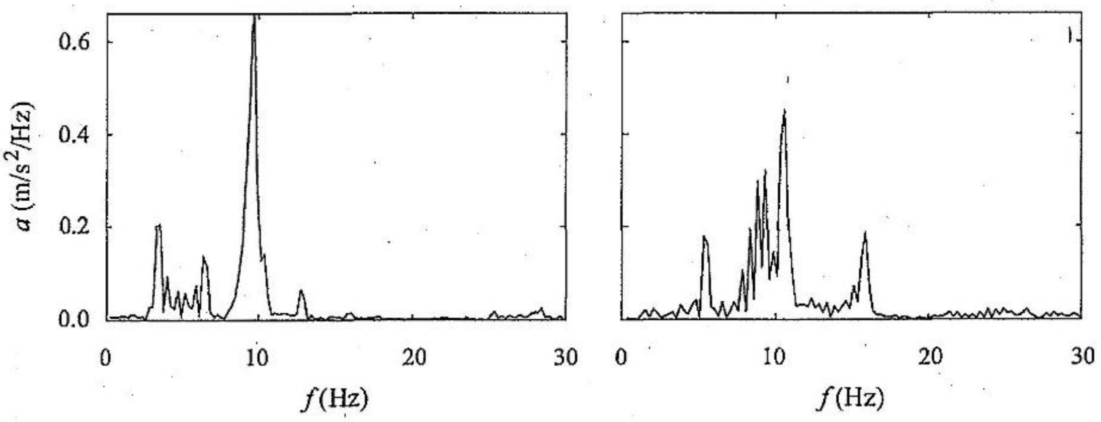

Figure 5: Spectrum of the response of a short-span bridge a) to a S103 (ICE3) train with $v_T = 280$ km/h, and b) to a S130 (Talgo) train with $v_T = 250$ km/h, measurements in Spain [13].

3 Different train speeds and amplitude-speed relations

During the test runs, the trains run with different speeds. The ICE3 run with 250 to 320 km/h while the Thalys run with 200 to 250 km/h. The corresponding ground vibrations are shown in Figure 6 for the highest and lowest speed of each train. A certain low-frequency range, which is located between the two axle-distance minima, can be found in all spectra. For each increase of the train speed, this ground vibration component is shifted to the next one-third octave frequency and the amplitudes are clearly increased. The same shift in frequency and increase of amplitude can be observed for the 8 Hz (10 Hz) peak of the ICE3 train. The amplitude-speed relation can be evaluated for each of the two trains as $A \sim v_T^{1.0}$ and $A \sim v_T^{2.0}$

Many different amplitude-speed relations can be measured. For the excitation by irregularities and for the low frequencies the increase should be at least $A \sim v_T^{2.0}$. An irregularity of a certain wavelength is shifted to a higher frequency with increasing speed. The corresponding acceleration of the wheelset and the related excitation force of the ground vibration increase with $v_T^{2.0}$. In addition to this vehicle-track transfer function, the transfer function of the soil must be observed. The relation between the excitation force and the particle velocities of the soil is increasing with frequency or train speed in case of a homogeneous soil (as for the present site), but can vary considerably for layered soils. This has been studied for two layered soils in [15]. Moreover, if other excitation components than irregularities are analysed, other amplitude-speed relations will follow. The weak increase with train speed in [3] seem to be due to a special soil layering where the main ground vibration components are above the layer frequency.

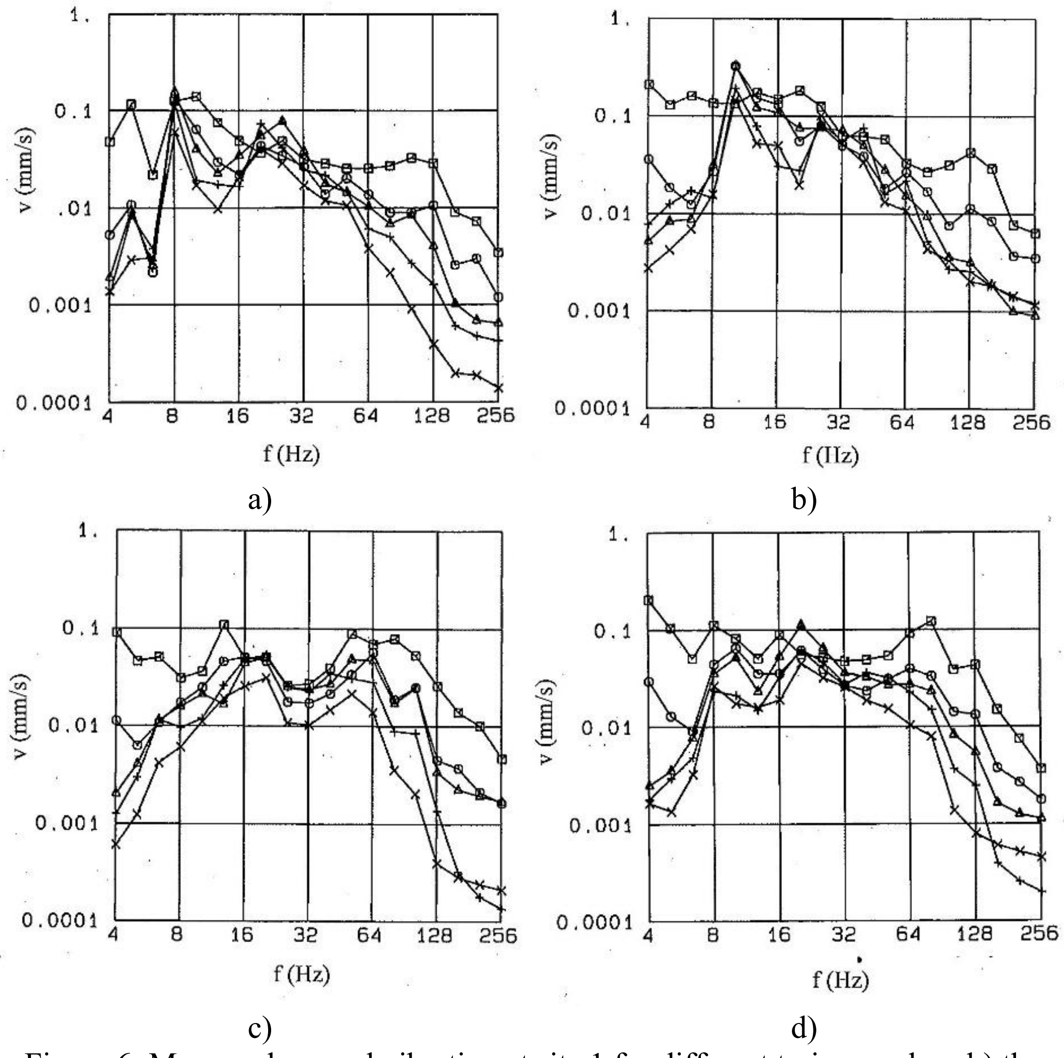

Figure 6: Measured ground vibration at site 1 for different train speeds, a,b) the ICE3 train with $v_T = 250$ (a) and 320 km/h (b), c,d) the Thalys train with $v_T = 200$ (c) and 250 km/h (d), one-third of octave band spectra at distances $r =$ □ 4 m, ○ 8 m, △ 16 m, + 32 m, × 64 m.

4 Different measuring sites and different soils

During the measuring campaign, measurements at two sites have been done. The transfer functions of the two soils have been determined by hammer tests. The resulting transfer functions (admittances) are shown in Figure 7a,b. The transfer functions have been approximated in the simplest way by a homogeneous half-space (Fig. 7c,d). The measured results show two specific details. At first, site 1 has a little higher amplitudes at low frequencies and that means that the soil is a little softer. Secondly, site 2 shows strongly differing spectra at high frequencies, and that means a strong material damping. Accordingly, the equivalent half-spaces have the parameters, shear wave velocity $v_S = 170$ m/s and material damping $D = 1$ % for site 1, and $v_S = 200$ m/s and $D = 3$ % for site 2.

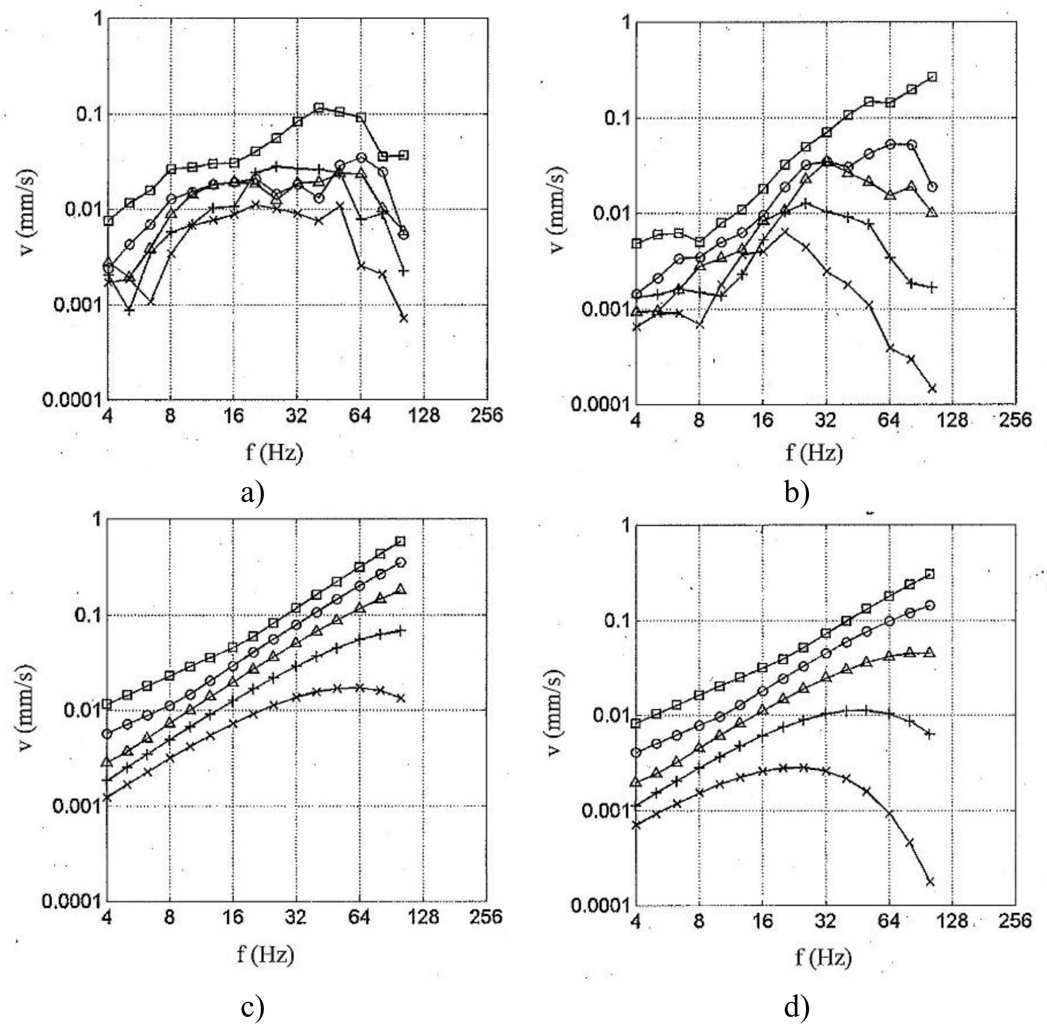

Figure 7: Transfer functions (admittances) of two different soils, a) measured at site 1, b) measured at site 2, c) calculated for a homogeneous soil with v_S = 170 m/s and D = 1 %, d) calculated for a homogeneous soil with v_S = 200 m/s and D = 3 %, one-third of octave band spectra at distances r = □ 4 m, ○ 8 m, △ 16 m, + 32 m, × 64 m.

Figure 8 shows the ground vibrations at both sites due to the same train with the same train speed. The differences are even stronger than the differences of the transfer functions. To make a proper comparison the measurements of different sensor positions are concentrated in one spectrum. This is shown in Figure 8c as the average spectrum for a distance of 8 m from the track. And the specific response of the soil should be eliminated for a proper comparison. This is done by calculating an equivalent force spectrum as described in [9]. The force spectra are independent from the specific soil. After these evaluation steps (Fig. 8d), the differences between the two measurements are smaller, but still there. These differences are due to the different track forms at site 1 and site 2, there is a ballast track at site 1 and a slab track at site 2.

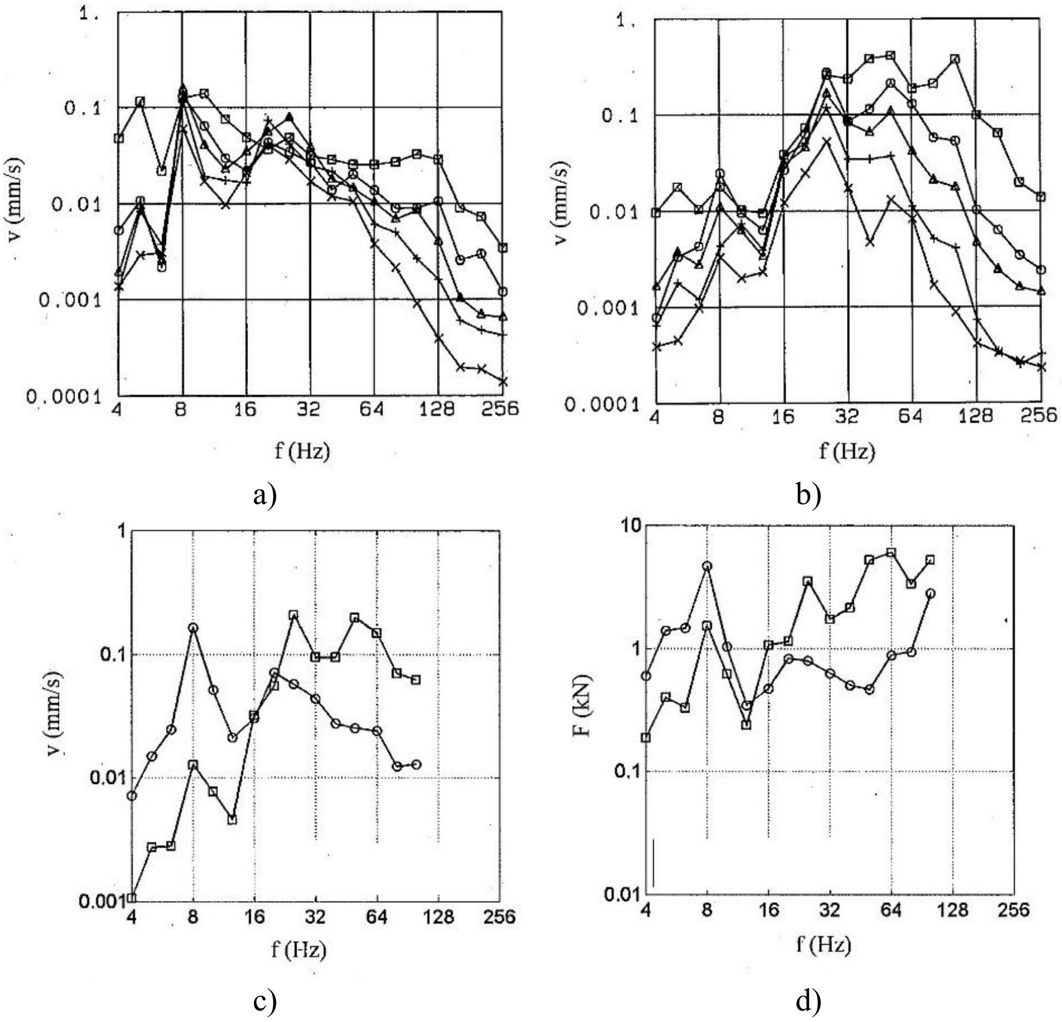

Figure 8: Measured ground vibration due to an ICE3 train with v_T = 250 km/h, a) at site 1, and b) at site 2, one-third of octave band spectra at distances r = □ 4 m, ○ 8 m, △ 16 m, + 32 m, × 64 m, c) reduced to the spectrum of the 8 m point, d) reduced to an excitation force spectrum, □ slab track, ○ ballast track.

5 Comparison of ballast and slab track

5.1 Measurement of different tracks at different sites

The different ground vibrations from the passage over a ballast or a slab track are shown in Figure 8a,d and Figure 9. For the slab track, the low-frequency ground vibration is much smaller than for the ballast track. In the mid-frequency range, the amplitudes of the slab track are strongly increasing and at high frequencies, the ground vibration of the slab track are much higher than for the ballast track which has more or less constant amplitudes in the whole frequency range up to 100 Hz. These characteristics are not pure chance as has been proved from additional measurements at two more sites at the same railway line. The additional results from TU Berlin and

German Railways (DB) in Figure 9 show exactly the same phenomena, although the second slab track site was 30 km away. The following sub sections will give possible explanations for the low-frequency reduction and the high-frequency amplification of the slab track.

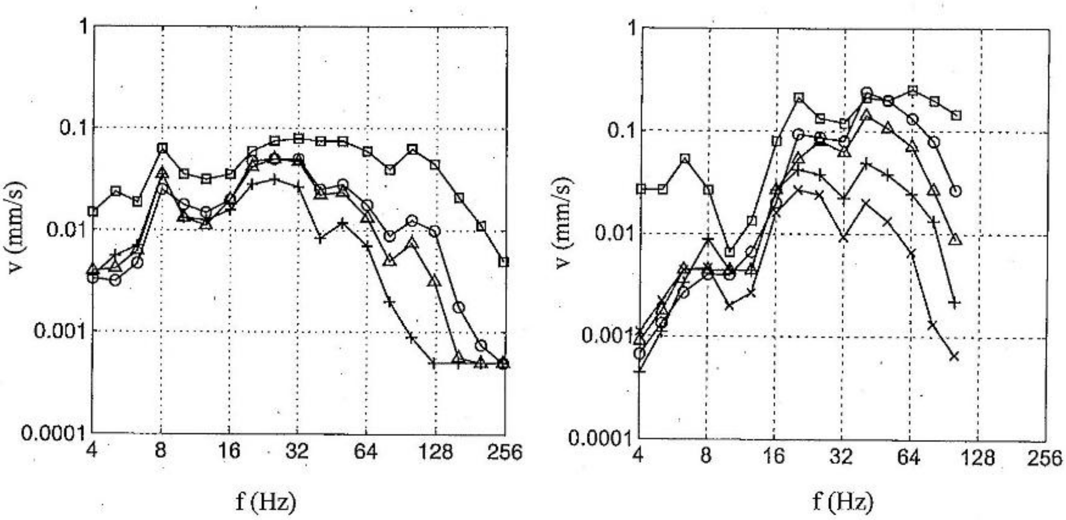

Figure 9: Ground vibrations induced by the passage of an ICE3 train with $v_T \approx 250$ km/h, one-third octave band spectra near a) a ballast track at site 3, r = □ 6, ○ 16, △ 32, + 64 m [16], b) a slab track at site 4, r = □ 6, ○ 12, △ 24, + 48, × 96 m [17].

5.2 The low-frequency reduction by slab tracks

One possible explanation of the low-frequency reduction is related to the static axle loads. The static axle load is distributed on a larger area by the stiffness of the track. When the static axle load is passing over a certain track point, the distribution along the track yields an axle impulse in time domain. The softer ballast track yields a stronger and shorter impulse (Fig. 10a) whereas the stiffer slab track yields a weaker and longer impulse (Fig. 10b). The thickness of the track plate makes the axle impulse considerably wider (Fig. 10b). The stiffness of the soil makes the axle impulse sharper (Fig. 10a). These effects can also be expressed in frequency domain. The spectra of the different axle impulses have different bandwidths. The bandwidth is narrower if the soil is softer (Fig. 10c) or if the track plate is stiffer (Fig. 10d).

The axle impulse on a slab track has a reduced band width compared to the ballast track. The filter effect of the stiff track plate is in a frequency range which is important for the ground vibration. In [18] it has been shown that the scattering of the axle impulses in a soil with randomly varying stiffness can generate an important low-frequency ground vibration for a ballast track. The filtering of the axle impulses by the stiff slab track could explain the reduction of this train-induced ground vibration component.

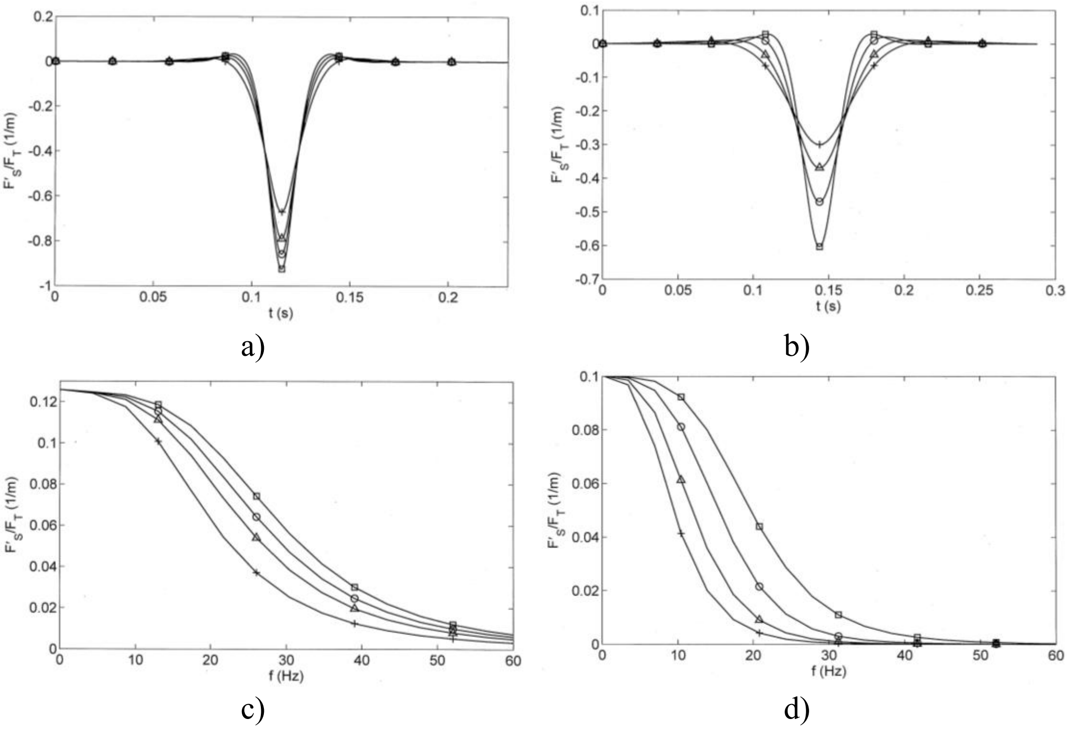

Figure 10: Axle-impulses a,b) in time domain, and c,d) in frequency domain,
a,c) ballast track on different soils with v_S = □ 300, ○ 200, △ 150, + 100 m/s,
b,d) slab track with different plate thicknesses □ 0.15, ○ 0.3, △ 0.45, + 0.6 m.

5.3 The high-frequency amplification of slab tracks

In the high-frequency part of the ground vibrations, the vehicle-track resonance falls. The vehicle-track resonance stems from the mass of the wheelset and the dynamic stiffness of the track under the wheelset. The stiffness under the wheelset is quite similar for the ballast and the slab track. This is achieved by soft railpads in the stiffer slab track. The main difference between ballast and slab track lies in the damping of the track-soil system. The ballast track has the strong damping due to the radiation into the soil. As the slab track has its resilience from the rail pads, the damping comes only from the material damping of the rail pads. The effect of the high and low damping can clearly be seen in the vehicle-track transfer functions in Figure 11. The low damping of the slab track yields strong vehicle-track resonances (Fig. 11b). The resonance frequency is ruled by the stiffness of the railpads. The highly damped ballast track shows only minor resonance amplifications (Fig. 11a).

Figure 11c,d shows measurement results from another site [4]. Axle-box measurements give the accelerations of the wheelset. The different vehicle-track resonances of the ballast and the slab track can be clearly seen. The results are for different train speeds, and the fixed vehicle-track resonance of the slab track can be observed, contrary to some speed dependent excitation frequencies of the ballast track, for example at 32, 40, 50, 63, 80 Hz the sleeper distance component. Moreover, these axle-box measurements show the high frequency amplification as well as the low-frequency reduction of the slab track.

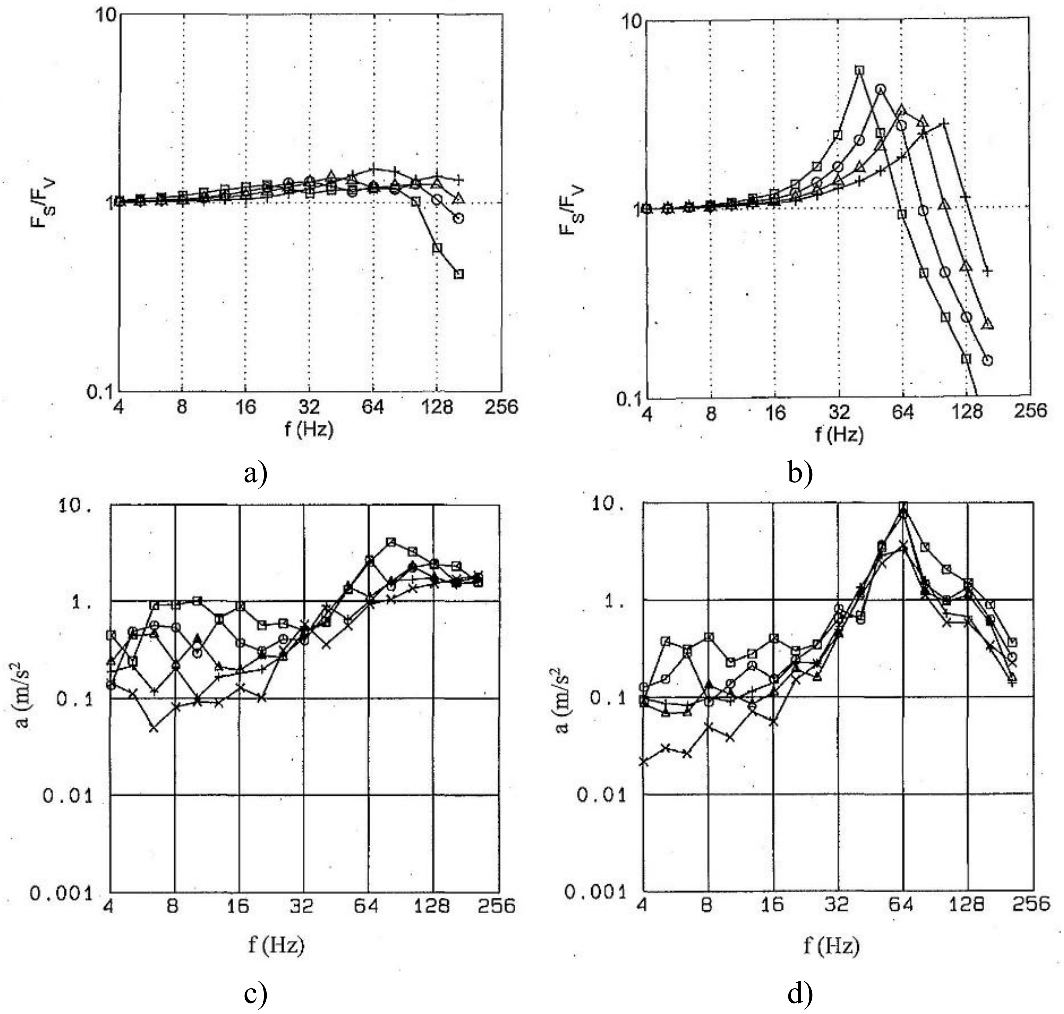

Figure 11: Vehicle-track interaction, calculated force transfer functions for a) the ballast track, soil and ballast with v_S = □ 100, ○ 150, △ 200, + 300 m/s, and b) the slab track with rail pad stiffness □ 20, ○ 40, △ 80, + 160 kN/mm. Measured wheelset accelerations at c) ballast track and d) slab track, one-third of octave band spectra for different train speeds v_T = □ 63, ○ 80, △ 100, + 125, × 160 km/h [4].

6 Conclusions

Measurement results have been shown for ballast and slab track sites at a high-speed line in Germany. The influence of the train (the axle sequence), the train speed, the soil and the track has been analysed. The experimental results and findings have been theoretically explained.

1. Regular axle sequences yield regular axle-sequence spectra with sharp peaks which are multiples of the car frequency. The car frequency is the only axle-distance frequency which can be noticed in the ground vibration. The axle distance in a bogie yields two characteristic minima of the axle-sequence and the ground vibration spectra.

2. At the present site and for the high-speed range of 200 to 320 km/h, the ground vibration amplitudes increase with train speed as $A \sim v_T{}^{1\ldots2}$. The amplitude-speed relation depends on the soil which is almost homogeneous at the measuring site.
3. The stiffness, wave velocity or transfer function of the soil of a measuring site must be determined. Otherwise results of different sites cannot be compared. The best way to make measurement results comparable is to calculate excitation force spectra which are almost free from special soil influences.
4. Slab tracks show a specific low-frequency reduction and a specific high-frequency amplification compared to a ballast track. Explanations have been given by the filtering of the axle loads and the less damped vehicle-track resonance.

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